for FOAM towards the present and expansion of the positive mass balance areas, mainly due to decreased snow ablation; in CSM the opposite trend occurs but changes are smaller and less systematic. The result from FOAM shows that the likelihood of ice sheets developing on the Tibetan Plateau may have increased since 11000 years ago, which is consistent some glacial records.

### C22B-07 1740h

## Possible Asynchronous Glacial Expansion During Climatic Warming in the Holocene, Glacier Bay Region, Alaska

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Glacial expansion is commonly thought to occur during cold climatic periods whereas thinning and recession follow as the climate warms. However, data from Glacier Bay, Alaska, on the location and timing of ice margin positions suggest that ice growth of the terrestrial and tidewater systems continued long after warming began. Radiocarbon dating of trees overridden by glacial advance provide rates and positions of ice margins over the last 9500 years BP. Major periods of ice advance were initiated prior to 9500 yrs BP and continued through at least 6000 yrs BP. Similarly ice returned to the region around 4900 yrs BP and continued to expand apparently without interruption through 3200 yrs BP. Data from more recent periods of ice advance are not as well constrained but appear to suggest ice filled much of the bay, perhaps including parts of the ice mass remaining from the 4.9 K advance, during three separate periods including the Little Ice age. Current investigations are evaluating signals in the tree ring record for causes, including signals developed by external forcings such as El Nino, the Pacific Decadal Oscillation (PDO) and Arctic Oscillation(AO).

### C22B-08 1755h

## Oases on Snowball Earth: Confluence of Ice Dynamics Modeling and Geological Observations

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Recent model experiments suggest that marine ice dynamics are important in the initiation and development of a snowball Earth. Ice-line advance is facilitated by the transport of latent heat and freshwater associated with Ekman forcing in the zone of westerlies (Lewis et al., 2002 this meeting) and with equatorward glacial flow of thick, multi-annual, marine ice (Goodman and Pierrehumbert, 2002 this meeting). After ice lines meet at the equator (snowball Earth), continued invasion by marine glaciers from higher latitudes maintains tropical marine ice >2.25 times thicker (<450 m) than static ice at thermal dynamic equilibrium (G & P, 2002). The dynamics imply that the tropical ocean will remain ice covered even after rising atmospheric $pCO_2$ drives tropical sea surface temperatures to the melting point. However, landfast marine ice on low-latitude continental shelves and inland seas that are protected from invasion by marine and terrestrial glaciers will melt away, creating 'oases' on a snowball Earth. Snowball oases should occupy a small fraction (<5%) of the global surface area but they might significantly enhance water vapor transport and accumulation rates of adjacent terrestrial glaciers. Despite acidification by high $pCO_2$, warming may cause critical oversaturation with respect to calcite or dolomite in snowball oases that are buffered by carbonate-rich bedrock and glacial debris (Fairchild, 1994). As snowball oases are small pools of water in contact with a $pCO_2$-rich (>0.1 bar) atmosphere, the carbon isotopic composition of any carbonates they precipitate should evolve accordingly. Initially, oasis water may resemble evolved snowball seawater, which will be dominated by hydrothermal activity buffered by dissolution of seafloor carbonate (Higgins and Schrag, G-cubed, 2003). Oasis water should evolve rapidly towards equilibrium with the atmospheric reservoir, whose isotopic composition is set by volcanic outgassing, not by the ocean. Oasis carbonate strata should exhibit a rapid rise in $\delta^{13}C$ with time, and may well have values substantially greater than 0 per mil PDB. We believe there are numerous examples of snowball oases in the geologic record associated with the Neoproterozoic Sturtian and Marinoan glaciations. Examples in NE Svalbard, SW Oman, SE California, and central and South Australia are well documented. In all but the first, the lithologic and isotopic evidence has been cited as precluding a snowball Earth altogether. In contrast, we consider that oases are a natural and important part of the snowball Earth cycle. Our concept of snowball oases combines insights from geophysical modeling and geology.

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# C31A MCC: 3010 Wednesday 0800h

## NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) Mission: Scientific and Technological Achievements I *(joint with A, B, G, H, OS)*

***Presiding:*** **H J Zwally,** NASA Goddard Space Flight Center**; B E Schutz,** Center for Space Research, University of Texas at Austin**; C A Shuman,** NASA Goddard Space Flight Center

### C31A-01 0800h INVITED

## NASA's Ice Cloud and Land Elevation Satellite (ICESat): Advancing Our Understanding of Ice and the Earth System

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As part of NASA's mission to "Understand and protect our home planet" the Earth Science Enterprise's cryospheric sciences program has as its primary focus understanding what changes are occurring in the mass of the Earth's ice cover, and the relationships between the Earth's dynamic ice and the rest of the Earth System. Recent observations using a comprehensive suite of both spaceborne and airborne instruments developed within NASA's Earth Science Enterprise and through our interagency and international partnerships have revealed the very complex and spatially variable behavior of the Earth's great ice sheets, with some very dynamic areas losing mass rapidly while others regions show positive mass balance. Recognizing that a tremendous amount of information about an ice sheet's behavior is manifest in its shape and how that shape changes with time, NASA's ICESat mission is designed to precisely measure ice elevations and elevation changes to determine the ice sheets' contributions to sea level and understand the mechanisms that govern those contributions. With a 94-degree inclination and pulsing at a rate of 40 times per second, ICESat provides measurements all over the world at 170-meter intervals along-track, with centimeter-scale accuracy over the ice and meter-scale accuracy on land. As such, detailed topographic measurements that were previously unachievable can be obtained the world over. While other remote sensing instrumentation provides critical spatial information, ICESat represents a groundbreaking mission that has as its focus measurements in the critical vertical dimension utilizing tremendous advances in laser ranging capabilities, orbit determination, and pointing accuracy. The ICESat mission will provide unprecedented insight into the behavior of ice, land cover, cloud characteristics, as well as some promising insights into the behavior of other geophysical systems.

### C31A-02 0815h INVITED

## Overview of ICESat's Laser Measurements of Polar Ice, Atmosphere, Ocean, and Land

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NASA's Ice, Cloud and Land Elevation Satellite (ICESat) mission was designed to measure changes in elevation of the Greenland and Antarctic ice sheets, vertical distributions of clouds and aerosols globally, land topography, vegetation canopy heights, and sea-ice elevations. Time-series of ice-sheet elevation changes will enable determination of the present-day mass balance of the ice sheets, study of associations between observed ice changes and polar climate, and estimation of the present and future contributions of the ice sheets to global sea level rise. ICESat was launched in January, 2003 and acquired science data for about 36 days from February 20 to March 29 with the first of three lasers of the Geoscience Laser Altimeter System (GLAS). Data acquisition with the second laser is scheduled to commence in mid-September. GLAS has a 1064 nm laser channel for surface altimetry with a designed range precision of about 10 cm. Vertical distributions of clouds and aerosols with 75 m resolution have been obtained with the 1064 nm channel and will be obtained with the more sensitive 532 nm channel after the 532 nm detectors are turned on in September. The laser footprints are about 60 m on the surface and are spaced at 172 m along-track. The on-board GPS receiver enables radial orbit determinations to an accuracy better than 5 cm. The star-tracking attitude-determination system should enable footprints to be located to 6 m horizontally when attitude calibration is completed. The orbital altitude is around 600 km at an inclination of 94 degrees with a 8-day repeat pattern for the calibration and validation period. After laser 2 is turned on, another 8-day cycle will be completed before going to a 91-day repeat orbit with a 33-day sub-cycle. The spacecraft attitude is planned to be controlled to point the laser beam to within ± 35 m of reference surface tracks over the ice sheets and to point off-nadir up to 5 degrees to targets of interest. ICESat was designed to operate for 3 to 5 years and was intended to be followed by successive missions to measure ice sheet changes for at least 15 years. Results from the initial 36 days of ICESat data demonstrate a unique capability to measure ice and land elevations with unprecedented accuracy, measure the vertical distributions of clouds and aerosols with an unprecedented sensitivity and global detail, measure vegetation canopy heights, and the elevations of sea ice. Data to be acquired at intervals of six months with the additional lasers should demonstrate the capability to measure ice sheet elevation changes to the planned accuracy of 1 cm/year, observe seasonal and interannual changes in global cloud cover, and other laser-unique capabilities.

C

### C31A-03 0830h INVITED

## ICESat Laser Altimetry: Calibration/Validation

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The Geoscience Laser Altimeter System (GLAS) was launched on ICESat in January 2003 into a 600 km altitude, near polar orbit from Vandenberg, California. The GLAS instrument has been developed by NASA Goddard and it was mated to the spacecraft bus, built by Ball Aerospace, in June 2003. GLAS laser-1 was activated in orbit on February 20, 2003 and elevation profiles of the Greenland and Antarctic ice sheets, as well as land and ocean profiles, have been produced using the 1064 nm wavelength. The laser pulse has a divergence of about 0.11 mrad, which illuminates a spot on the surface with a 66 m diameter. The 170 m spot separation on the surface is determined by the ICESat orbital motion and the 40 Hz laser pulse repetition rate. Unlike wide pulse radar altimeters, accurate knowledge of the laser beam direction is required for the laser altimeter to produce accurate surface profiles. The laser pointing direction is determined with the assistance of an innovative system of CCD cameras plus calibration/validation methodologies. The combination of the laser pulse round trip time of flight and the pointing determination system provides an altitude vector. Determination of the direction of the altitude vector has an accuracy requirement of about 1.5 arcsec (or about 4.5 m on surface). In addition to the instrumentation required to produce the altitude vector, the position of a GLAS reference point with respect to the center of mass of the Earth is required. The ICESat BlackJack GPS receiver from NASA JPL has enabled determination of the radial component of the orbit to a few centimeter accuracy level. Laser-1 operated in orbit with a ground track that was controlled to within 800 m of an 8-day repeat reference track. During laser-1 operation and after the laser ceased firing on March 29, experiments were conducted to assess and improve the accuracy of off-nadir pointing, a unique capability to enhance the science return. This paper will provide an assessment of the accuracies achieved by laser-1 and during laser operations with the additional GLAS lasers. On-orbit factors, such as thermal and jitter effects, that may limit the achieved accuracy will be discussed. These assessments will draw on calibration/validation experiments that have been conducted as well as the analysis of the on-board instrumentation.

### C31A-04 0845h

## ICESAT/GLAS Reveals Ice Sheet Surface Features at Ice Stream Shear Margins in West Antarctica.

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The shear margins surrounding ice streams are marked by grooves and ridges in the ice surface. These scars remain after ice streams become inactive, recording the structure of the ice streams, and allowing investigations of the history of the ice stream system. The positions of the scars are readily found in satellite imagery of WAIS, but the character of the surface undulations is more difficult to determine. NASA's GLAS (Geoscience Laser Altimeter System) mission has produced several thousand kilometers of high-resolution elevation profiles over the West Antarctic ice streams. These profiles reveal the shape of the margin scars at high vertical and horizontal resoultion. Here I examine the marginal features of both active and passive ice streams, and track their evolution from the inland tributary region to the Ross Ice Shelf. I find the horizontal position of the marginal features using AVHRR (Advanced High Resolution Radiometer) and SAR (Synthetic Aperture Radar) imagery, and determine their vertical structure from GLAS data. Three main factors contribute to the formation of marginal features: The change in basal drag at the edge of the ice stream produces a break in the surface slope. The high strain rate associated with fast flow in the margin produces an effective softening of the ice, leading to flattening of the surface. Changes in the elevation and width of the ice stream produce slope breaks at the outside of the margin where slow-moving ice cannot rapidly respond to changing boundary conditions. I present the results of finite element modeling demonstrating the surface characteristics associated with these three processes and relate them to the features seen in the ice sheet.

### C31A-05 0900h

## Atmospheric and Surface Reflectance Measurements by the Geoscience Laser Altimeter System

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The Geoscience Laser Altimeter System launched in early 2003 is the first satellite instrument in space to globally observe the distribution of clouds and aerosol through laser remote sensing. The instrument is a basic backscatter lidar that operates at two wavelengths, 532 and 1064 nm. The mission data products for atmospheric observations include the calibrated, observed, attenuated backscatter cross section for cloud and aerosol; height detection for multiple cloud layers; planetary boundary layer height; cirrus and aerosol optical depth and the height distribution of aerosol and cloud scattering cross section profiles. The data will enhance knowledge in several areas of atmospheric science: the distribution, transport and influence of atmospheric aerosol, significantly more accurate measurements of the coverage and height of cirrus and other clouds, polar cloud climatology and radiation influence, the dynamics planetary boundary layer and others. An overview and summary of initial results are presented. Initial results from the first months of operation show the detailed height structure of clouds and aerosol on a global basis as expected. The 532 nm channel was expected to be the more sensitive and primary channel for aerosol measurements, but extensive aerosol loading in many regions are observed by the 1064 nm channel. Sensitivities are down to a few times 10-6 1/(m-sr), much better than originally expected. The 532 channel adds an order of magnitude addition sensitivity. Initial comparisons to aerosol models have been done. Similarly for global cloud cover, good results are obtained just from the 1064 nm signal and from both channels, a measurement of multiple layers and cloud overlap has been made. Antarctica observations show high levels of total cloud cover including unique low-level cirrus and blowing snow. Data products have been generated for cloud, aerosol and PBL presence and heights in addition to the basic scattering cross section profiles. The received reflected energy of the laser pulse from the surface has applications to characterize atmospheric parameters. The surface pulse reflectance is a function of the atmospheric transmission and the surface properties. The calibration of the surface reflectance and atmospheric transmission retrievals has been analyzed through surface based intercomparison measurements. Pulse reflectance over oceans has been related to wind speed with results that are in agreement with predicted values. Multiple scattering of photons is an important factor for the effective atmospheric transmission, especially for transmissive clouds, and analysis of surface signals provide a test of model generated corrections. Stretching of pulses due to cloud and aerosol scatting is also an important factor for the accuracy of the surface altimetry and the clearing and correction of scattering errors has been initially evaluated.

URL: http://virl.gsfc.nasa.gov

### C31A-06 0915h

## ICESat Observations of Forest Canopy Height

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The Ice, Cloud and Land Elevation Satellite (ICESat), a component of the NASA Earth Observing System, was launched into orbit on January 12th, 2003. The ICESat mission acquires globally distributed profiles with the Gesoscience Laser Altimeter System (GLAS), providing observations of ice sheet elevation, cloud and aerosol heights, land topography and vegetation characteristics. Vegetation height is a key indicator of the amount of above-ground carbon stored in forests, which is an essential component in the cycling of carbon dioxide between the Earth's atmosphere and land surface. Vegetation height is also a useful indicator of forest age and habitat quality. Traditional orbital remote sensing methods are not well suited to measure vegetation height. The laser altimeter waveforms recorded by the GLAS instrument provide a global means to sample the height of vegetation along the ICESat profiles. In forested areas where the ground is flat or gently sloping, we observe that the waveforms record the laser pulse reflected from vegetation and, slightly later in time, the reflection from the ground. The time difference between these two echoes yields a direct measurement of maximum canopy height. As anticipated, in areas of steep terrain, the vegetation and ground returns become mixed together in the waveforms, making the analysis more difficult and requiring independent information on ground slope at the laser footprint location. We illustrate waveform retrieval of canopy height for low slope settings for several forest ecosystems, and validate the GLAS height retrievals for Pacific Northwest forest stands using a technique that matches observed and simulated waveforms where extensive high-resolution airborne laser mapping of ground topography and vegetation height is available.

### C31A-07 0930h

## Sea Ice Elevation From ICESat/GLAS Laser Altimetry

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Arctic sea ice is currently in a state of change. Such changes in sea ice thickness and extent can be used to assess polar climate variability. Observational records suggest that over the past few decades a substantial decline in sea ice extent together with rapid thinning have occurred. Continuous monitoring of sea ice thickness has however proved to be a more difficult task than measuring ice extent and no data sets cover the entire Arctic. Recent research shows that radar altimetry from the ERS satellites can successfully be used to measure sea ice freeboard, from which ice thickness can be estimated. However the exploitation of this data is limited to some extent due to the large radar footprint (10km), and limited latitudinal coverage (to 81.5°). In addition all satellite altimeter estimates suffer inaccuracies due to uncertainties in snow loading on sea ice. The Geoscience Laser Altimeter System (GLAS) extends satellite altimetric coverage of sea ice to 86° latitude for the first time. In addition, the much smaller laser footprint (70m) provides improved resolution of sea ice and ocean topography. On the other hand, laser altimetry data is more susceptible to atmospheric effects such as cloud cover and forward scattering of laser pulses. Using data from the first month of operations, we examine the feasibility of deriving sea ice elevation from GLAS altimetry data. We investigate the influence of instrument errors and environmental effects (e.g. pulse broadening from clouds) on the accuracy of GLAS elevation measurements. We compare GLAS elevations over sea ice to a state-of-the-art Arctic geoid model and to a mean sea surface derived from ERS radar altimetry data. We analyse the characteristics of laser waveforms and compare these with available *in situ* data. Finally, we compare GLAS sea ice elevations with sea ice freeboards and thickness derived from ERS data. By combining these two datasets, the potential exists to obtain estimates of snow loading and hence more precise estimates of sea ice thickness.

# C31B MCC: Level 1 Wednesday 0830h

## Advances in Glacier Geophysics II Posters *(joint with G, H, OS, PP)*

***Presiding:*** **B Kulessa,** Queen's University of Belfast**; T Murray,** University of Leeds

### C31B-0394 0830h POSTER

## Estimating the Depth and Shape of Lake Vostok's Water Cavity from Aerogravity Data

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The water circulation within Lake Vostok provides a viable mechanism for transporting mass and energy through the lake, enhancing the potential for the support of biota. The circulation pattern depends primarily on the geometry of the lake bathymetry. Water in shallow regions will warm more from the geothermal heat flux than in deeper parts, resulting in subtle lateral changes of water density. This temperature-induced change in water density is the primary driving force for the horizontal circulation within the lake. To date, only a few seismic soundings have provided estimates of the water depth of Lake Vostok. To determine the depth and shape of the water cavity over the entire lake we use gravity data acquired along a grid of flight lines traversing the region. The free-air gravity anomaly field reflects density variations related to both major geological and topographic structures and changes in the water depth of the lake. The gravity contribution from the deeper geological structures can be removed from the free-air anomaly by low-pass filtering of the data. The subglacial topography outside the lake and the geometry of the overlying ice sheet are well constrained from ice-penetrating radar measurements. The unknown parameter that dominates the filtered gravity anomaly is the relief of the bedrock-water interface. Assuming a constant density contrast across this boundary, the gravity data can be inverted for the bathymetry of the lake. The results show that Lake Vostok consists of two sub-basins, a northern and southern. The southern sub-basin is much deeper and approximately double the spatial area of the smaller northern sub-basin. The two sub-basins are separated by a saddle with very shallow water depths. The separation of Lake Vostok in two distinct sub-basins has important ramifications for the water circulation within the lake. The lake volume estimated from the inversion of gravity data is 5200 cubic km, three times bigger than previously thought. The melting and freezing pattern observed from ice-penetrating radar data is intimately linked to the bathymetric structure of the lake. Over the northern basin, basal melting is dominating while over the southern basin, basal freezing dominates the lake/ice interaction. For a fresh-water scenario, basal meltwater in the northern basin would sink to the bottom. For this reason the water exchange between the two basins is probably very limited and raises the possibility that the two separate basins have